Chapter 2

Power Distribution Systems

Distribution networks have typical characteristics. The aim of this chapter is to give an idea about global distribution networks design and establish the distinction between country and urban distribution networks. In a conclusion, the state of the art in load flow and state estimation calculations related to distribution networks is described. The problem of power consumption estimation is then introduced.

2.1-Global Design of Distribution Networks

The electric utility system is usually divided into three subsystems which are generation, transmission, and distribution. A fourth division, which sometimes is made, is subtransmission. However, the latter can really be considered as a subset of transmission since the voltage levels and protection practices are quite similar.

The distribution system is commonly broken down into three components: distribution substation, distribution primary and secondary. At the substation level, the voltage is reduced and the power is distributed in smaller amounts to the customers. Consequently, one substation will supply many customers with power. Thus, the number of transmission lines in the distribution systems is many times that of the transmission systems. Furthermore, most customers are connected to only one of the three phases in the distribution system. Therefore, the power flow on each of the lines is different and the system is typically 'unbalanced'. This characteristic needs to be accounted for in load flow studies related to distribution networks.

2.1.1-Distribution Substations

The distribution system is fed through distribution substations. These substations have an almost infinite number of designs based on consideration such as load density, high side and low side voltage, land availability, reliability requirements, load growth, voltage drop, cost and losses, etc..

For a typical substation, the voltage of the high side bus can be anywhere from 34.5 kV all the way up to 345 kV. The average high side voltage level is approximately 115 to 138 kV. Two or more feeders are normally connected to the low voltage bus through a feeder breaker.

2.1.2-Distribution Feeders

On a primary distribution feeder, various equipment can be distinguished such as fuses, distribution transformers, reclosers, switches. Much of these equipment, such as reclosers, are used only at the distribution level. Other equipment such as capacitors, transformers, and arresters are also used at the transmission levels but with considerably different rules of application.

Most distribution feeders are three-phase and four-wire. The fourth wire is the neutral wire which is connected to the pole, usually below the phase wires, and grounded periodically. A three-phase feeder main can be fairly short, on the order of a mile or two, or it can be as long as 30 miles. Actually, the length of feeders is closely linked with load density at location. For instance, for an area where the customer load density is strong, primary network will end very close of consumers and secondary feeders will be short. For a weak load density area, primary and secondary feeders will be longer. Distance separating substation from customers will be covered both by primary and secondary feeders in order to provide the best quality supply. These differences explain why a distinction is made between country distribution networks, where customers are spread, and urban distribution networks, where large urban agglomerations must be taken into consideration.

Some characteristics of the secondary spot network are going to be given because it is frequently used in the United States. Secondary spot network is characterized by a maximum service reliability and an operating flexibility. It includes two or more ‘transformer / protector’ units in parallel. The low voltage bus is continuously energized by all units, and automatic disconnection of any unit is obtained by sensitive reverse power relays in the protector. Maintenance switching of primary feeders can be done without customer interruption or involvement. This system represents the most compact and reliable arrangement of components and is the most reliable for all classes of loads.

2.1.3-Secondaries

The purpose of the distribution transformer is to reduce the primary voltage to a level where it can be used by the customer. Single-phase transformers range in size from 10 kVA to about 300 kVA with units in the 25 and 37.5 kVA size being the most popular for residential areas.

The secondary voltage level in the United States for residential service is 120/240 Volts. Lower wattage devices, such as lights, are connected line-to-neutral across both sides of the transformer secondary. Higher wattage devices, such as ovens, clothes dryers, etc., are usually connected across the 240 volt circuit since this has the effect of reducing voltage drop and losses.

2.2-Country and Residential Networks

The electrification of rural areas took place recently. Indeed, installation costs being in inverse ratio to population density, rural electrification had not and has not yet, in different places, found economical justification. Actually, it has been initiated in order to avoid rural depopulation on the one hand, and to provide country people with the same way of life as urban people on the other hand.

2.2.1-Secondary Country Networks

Rural electrification was developed step by step. Gradual improvements have been brought in order to reduce voltage drop following from continuous customer load increase. Actually, these improvements consisted of reinforcing existing secondary networks.

In the United States, country customers are considered in private, or in very small groups, and are fed by a single-phase distribution transformers. Thus, secondary network is limited, in most cases, to two or three customer connections. Let us specify that for residential areas, the means that are used are the same as those of country areas, except that each distribution transformer feeds eight or nine customers.

Now, underground distribution being commonplace, utilities are taking a slightly different structure. Transformers are located underground and they feed more customers who are distributed over a secondary loop.

2.2.2-Primary Country Networks

American primary networks, in rural or residential areas, have a radial topology. Close to substations, feeders are three-phase. However, as branches have only one or two phases, a neutral wire is needed from the beginning to the end of these feeders.

The voltage levels used are very different according to the region considered. Historically, 4 kV network was widely spread. Thus, in order to reinforce this network, another voltage step was added such as 12.8 kV or 13.5 kV or 18 kV, etc.. Presently, two tendencies dominate: the primary coil value for distribution transformers is $13.8/\sqrt{3}$ kV, and the step of 4 kV is reduced to individual transformers feeding.

In residential areas, under environmental pressures, much of the new construction, particularly the single-phase lateral construction, is being put underground. But general network features stay the same.

2.3-Urban Distribution Networks

2.3.1-Specific Requirements of Urban Networks

Large urban agglomerations are characterized by strong load density at location and by a real setting difficulty for most works. These characteristics are, however, closely dependent on the area considered inside agglomeration.

In downtown areas, distribution networks feed commercial and domestic loads, that is to say, a lot of utilities using either little power (lights for example) or average power (heating, ovens, etc..). They also feed large buildings which represent enormous load density (more than $550\ \mathrm{MW/km^2}$ inside Manhattan for instance).

In peripherical areas, loads are more diversified. We can underline on the one hand, industrial areas characterized by a strong and concentrate power requirements, and on the other hand, residential areas characterized by a high service reliability.

2.3.2-Secondary Urban Networks

These networks mostly consist of underground cables located under sidewalks. At crossroads, systems called ‘junction boxes’ permit the modification of network topology, in case of cable loss for example. In most cities, secondary is either a spot network (described above) or a grid network. Secondary AC network systems, or grid networks, began around the year 1915 replacing the older DC networks which had problems with the cost of converters, the cost of copper and voltage difficulties. The major segments of a grid network are: primary feeder circuits, network units (the network transformer and the network protector) and secondary grid. The secondary grid is 208Y/120. The main protection of the secondary grid comes from the ability of the system to ‘burn off’ the fault. This means that no protective device was required to operate.

REMARK: the network protector is an electrically operated low-voltage air circuit breaker with self-contained relays for controlling its operation. Its main purpose is to isolate the secondary from problems on the source side (network transformers, primary feeders, etc..).

2.3.3-Primary Urban Networks

In the US, two solutions have been chosen. One for residential areas, one for large urban agglomerations. In residential areas, substations are connected together through several feeders. Each feeder owns a circuit breaker located near the middle. Thus, the two different halves are fed by two different substations. In agglomeration, both high service quality and reliability require specific networks. Generation plants and network structure have to be accounted for. Generation plants should be located as near as possible from customer loads. However, pollution problems and more generally environmental problems required the building of power stations far from downtown areas.

2.4-Conclusion

Distribution networks make up the last link in the chain of supplying energy. There exists two different types of distribution networks: country and urban. Their density and their complexity are usually larger than for the transmission systems which feed them through distribution substations. Distribution networks also have specific characteristics which distinguish them from transmission networks. The main differences lie in the number of particular types of devices, multiphase possibilities and widely varying types of loads. Besides, most of these loads are connected to only one of the three phases and the system is commonly unbalanced. It is becoming apparent that current transmission systems programs based on specific transmission requirements, such that programs to solve load flow or state estimation problems, are inadequate for distribution systems. New programs need to be developed which include distribution networks specificity mentioned above. Over the years, some algorithms specific to radial systems have been presented (**[5], [7], [9], [10], [11], [12]**). Most of them are based on Newton-like methods and try to take full advantage of the radial structure of the distribution networks to save computation time.

These methods are very accurate and powerful. They assume, however, initial conditions to be reliable and usually do not take into consideration an important characteristic of distribution systems: the severe limitation to the number of telemetered variables. This means, they assume that all input variables are available. This assumption is not true for the moment. Some other papers deal with this characteristic (**[2], [3], [4]**). They propose an approach using a probabilistic formulation in order to define ‘probabilistic’ or ‘stochastic’ power flows. More precisely, the problem of unknown input variables is overcome with stochastic approach, by using random variables and applying methods from the probability theory. Past probabilistic power flows, aimed mainly at transmission circuits, incorporated the stochastic behavior of loads, but did not account for measurements. Furthermore, they assumed parametric shapes for the loads' distribution that are imprecise. The present load flow approach related to distribution networks is formulated as a probabilistic power flow which takes advantage of telemetered variables and the radial nature of distribution circuits. To sum up, traditional state estimation and load flow studies defined for transmission networks are replaced in distribution by load flow studies taking into consideration (i) the radial nature of these circuits and (ii) the exact values of complex powers and scheduled voltages at each metered node, and estimates of these values at each non-metered node.

The most important problem to solve, in order to carry out this last type of study, is to provide accurate values of power consumption where they are not metered. Even in the most recent papers, the methods proposed to overcome this obstacle are based on traditional parametric statistics which assume Gaussian parametric shapes for the load distributions. These distributions, however, are very asymmetric as it is seen in the next chapter and strongly depart from Gaussian distributions. Furthermore, they are quite different from one case to another one, depending on the load composition and the period of the year chosen. For all these reasons, it is not possible to utilize classical statistical methods to estimate the values of power consumption. A more reliable method must be used to provide the non-metered consumption values. A statistical method that does not assume any distribution was chosen to solve this problem: the bootstrap method.